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A STUDY IN HEAT TRANSMISSION

(THE TRANSMISSION OF HEAT TO WATER IN TUBES AS AFFECTED BY THE VELOCITY OF THE WATER)

BY

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UNIVERSITY OF ILLINOIS
ENGINEERING EXPERIMENT STATION

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A STUDY IN HEAT TRANSMISSION

I. Introduction[1]

The following experiments, preliminary in nature, were undertaken with two objects in view; (1) to determine the effect of the velocity of the flow of the water on the heat transmitted through the walls of tubes; (2) to determine if the methods of experimentation used were applicable and desirable for a more extensive investigation of the subject, provided this seemed justifiable by the results obtained.

In the flow of heat from a medium, gaseous or liquid, in contact with a metal plate, to a medium in contact with the opposite side of the plate, there are three resistances to be overcome; the two film resistances, that is, the resistance between the liquid and the plate on each side, and the resistance due to the metal of the plate. In the case of liquids in contact with metal plates, it will be found that the first two resistances are considerable as compared with the resistance of the plate itself, and also that these film resistances depend upon the nature of the medium in contact with the plate, and the relative movement or agitation between the plate and the medium. Owing, therefore, to the multiplicity of media and to the state of these media, as found in practice, it was considered advisable to endeavor to determine the rate of flow (or transmission) of heat as a function of the three factors, temperature of tube, temperature of water and velocity of water.

II. Description of Apparatus

The apparatus (Fig. 1) consisted of the steam jacket F provided with flanges and stuffing boxes at each end. The steam was admitted at C and bubbled up through the water in the jacket,

[1]Acknowledgment.—Credit is due Mr. A. P. Kratz for assistance in the taking of readings and in making the computations.

which was kept at a constant level, and then passed out the exhaust at D. The pressure of the steam in the jacket, and therefore the temperature, was maintained constant by placing a safety valve on the exhaust pipe, and allowing the steam to blow through this valve throughout the tests. The bubbling of the steam through the water prevented the possibility of superheat due to throttling at the valve C.

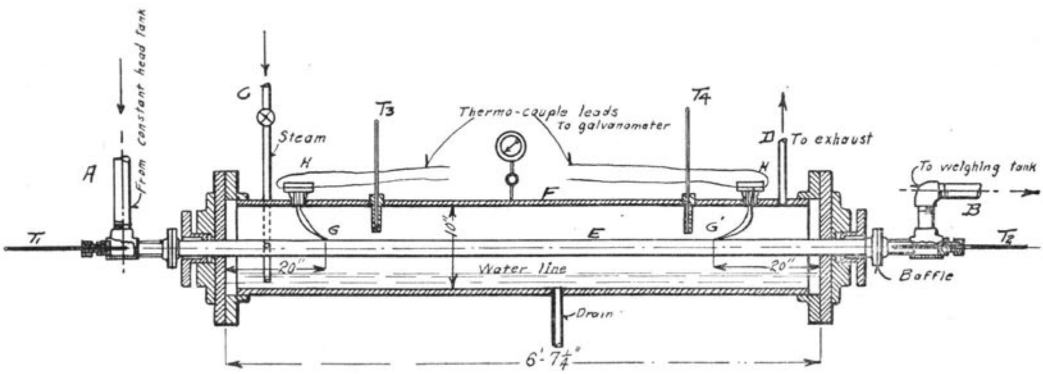


FIG I

TRANSMISSION OF HEAT THROUGH BOILER TUBES

The tube through which the flow of heat was measured was a 1-in. Shelby cold-drawn steel tube, outside diameter 1.253 in.; inside diameter .985 in., and walls .134 in. thick. This tube was centered through the steam jacket, as shown, and packed around the ends. Each end was threaded, and a flange coupling used to connect the tube on the entering end with the water supply pipe A, and on the discharge end with the swinging ell at B. Rubber gaskets ¼-in. thick were placed between these couplings; on the discharge end, a sheet metal baffle was inserted. Another baffle was inserted in the pipe A about 18 in. above the tee. The object of these baffles was to break up the stream lines before reaching the thermometers T_1 and T_2. This was done in order that the average temperature of the water might be determined. The couplings were drawn together with insulated bolts. The insulation, together with the gaskets, was used to prevent the conduction of heat back on the tube. The water supply was taken from a constant head tank, located about 25 ft. above the tube, which permitted a maximum velocity of about 17 ft. per second. The velocity through the tube was regulated to suit the demands by means of a throttle valve placed in the pipe *A*. The steam supply was taken from the laboratory mains.

III. Measurement of Temperatures

The temperature of the water, entering and leaving, was taken with mercury thermometers reading directly to tenths; these readings could be estimated to hundredths of degrees C. The thermometers were passed through the stuffing boxes and were in direct contact with the water. The baffles, above mentioned, insured the breaking up of the stream lines, so that very nearly the average temperature of the water was obtained. This was tested by changing the position of the thermometers.

The temperature of the steam was also taken with mercury thermometers T_3 and T_4, passed through stuffing boxes, so that their bulbs were in direct contact with the steam. Allowance was made for the error due to the pressure of the steam on the bulb. The drawing shows these thermometers placed in thermometer cups; the cups, however, were taken out before the regular experiments were begun and replaced by stuffing boxes.

The temperature of the steam wall of the tube was taken by means of copper-constantan thermocouples and a Siemens and Halske millivoltmeter. The couples were located at G and G', 20 in. from the face of each flange. The ends of the couples were soldered into small holes, about $\frac{1}{32}$ in. in diameter, and about $\frac{1}{64}$ in. deep, which were drilled in the surface of the tube. The leads were brought out through small glass tubing to the pipe flanges at *HH*, and then between two rubber gaskets placed between the flanges.

The mean temperature of the tube was taken as the average of the temperatures taken with the two couples, and is given in column 6 of Table 1. All readings were taken in Centigrade units and later changed to Fahrenheit.

TABLE 1

	Temperatures in Degrees F.										Water		Conductance				
No.	Entering Water Av.	Leaving Water Av.	Rise	Steam in Jacket	Steam Wall of Tube. Mean	Drop from Steam to Wall of Tube	Drop through Metal of Tube	Water Wall of Tube	Water in Tube. Mean	Drop from Wall of Tube to Water	Weight of Water per Minute	Velocity of Water in ft. per second	B. t. u. per sq. ft. per Minute	Conductance of Film on Steam Side	Conductance of Film on Water Side	Conductance of Tube and Film on Water Side	
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	
1	56.92	66.75	9.83	210.9					61.8		318.0	16.07	1615				
2	58.20	70.25	12.05	210.9					64.2		263.0	13.29	1638				
3	58.55	71.90	13.35	210.9					65.2		236.0	11.93	1628				
4	58.63	73.20	14.57	210.9					65.9		204.3	10.33	1538				
5	58.20	74.82	16.62	210.9					66.5		176.0	8.90	1512				
6	57.89	75.28	17.39	210.9					66.6		147.0	7.43	1322				A
7	58.20	78.52	20.32	210.9					68.4		120.0	6.07	1260				
8	58.29	84.49	26.20	210.9					71.4		81.1	4.11	1098				
9	58.37	92.00	33.63	210.9					75.2		55.1	2.80	957				
10	58.91	108.40	49.50	210.9					83.7		29.0	1.48	741				
11	60.10	175.49	115.40	210.9					117.8		7.12	.37	425				
1	58.55	73.35	14.80	273.6	181.2	92.4	35.2	146	65.9	80	331.7	16.78	2537	.458	.528	.367	
2	58.32	78.12	19.80	274.4	202.0	72.4	34.7	167	68.2	99	244.4	12.37	2501	.576	.421	.312	
3	58.15	75.45	17.30	273.7	193.2	80.5	36.5	157	66.8	90	294.3	14.89	2631	.544	.487	.347	
4	57.90	80.94	23.04	273.9	203.0	70.9	33.1	170	69.4	100	200.5	10.15	2387	.561	.399	.300	
5	58.03	85.83	27.80	274.1	208.0	66.1	31.0	177	71.9	105	155.7	7.89	2237	.561	.354	.273	
6	58.10	92.88	34.78	274.1	211.0	63.1	28.9	182	75.5	106.5	116.0	5.88	2083	.550	.325	.256	B
7	62.87	120.46	57.59	274.1	235.0	39.1	23.8	211	91.7	119	57.6	2.94	1715	.730	.240	.200	
8	63.28	108.50	45.22	274.5	227.0	47.5	24.8	202	86.0	116	76.4	3.89	1786	.628	.256	.211	
9	63.73	145.90	82.17	274.5	239.7	34.8	21.0	219	105.0	114	35.7	1.84	1516	.724	.222	.187	
10	67.55	162.20	94.65	274.4	243	31.4	19.0	224	114.0	110	28.0	1.45	1369	.724	.207	.177	
1	67.54	85.00	17.46	306.6	219.9	86.7	43.6	176	76.3	100	348.4	17.64	3144	.605	.525	.365	
2	67.54	87.19	19.65	306.6	219.0	87.6	43.2	176	74.4	102	306.4	15.50	3112	.591	.508	.357	
3	67.54	93.30	25.76	306.5	230.5	76.1	41.6	189	80.4	109	226.0	11.43	2998	.655	.459	.333	
4	58.73	107.69	48.96	306.8	246.4	60.4	36.7	210	83.2	127	104.7	5.33	2649	.731	.347	.269	C
5	58.89	118.05	59.16	307.0	252.3	54.7	34.7	217	88.5	129	81.8	4.17	2501	.761	.322	.254	
6	59.27	129.70	70.43	307.0	255.7	51.3	31.3	224	94.5	129	62.0	3.17	2256	.731	.291	.234	
7	59.52	154.35	94.83	307.4	261.1	46.3	28.8	232	107.0	125	42.5	2.19	2081	.750	.278	.226	
1	57.67	80.50	22.83	330.2	220	110.2	55.2	165	69.0	96.0	338.4	17.13	3995	.606	.694	.440	
2	57.67	83.88	26.21	330.0	229.4	100.6	52.0	177	70.8	106.0	277.4	14.05	3756	.621	.591	.396	
3	58.28	90.92	32.64	330.0	233.1	96.9	47.8	185	74.6	110.0	205.0	10.39	3455	.594	.524	.365	D
4	58.17	97.90	39.73	330.2	241.8	88.4	45.1	197	78.07	119.0	158.7	8.06	3260	.614	.457	.331	
5	58.50	120.60	62.10	330.2	257.4	72.8	37.0	220	89.5	130.5	83.3	4.25	2672	.611	.340	.265	
6	58.89	161.50	102.61	330.2	267.1	63.1	32.8	234	110.2	124.0	44.7	2.31	2370	.625	.318	.251	

IV. Observations

The velocity of the flow of the water through the tube was obtained by weighing the total amount discharged over a given period of time. This time was measured with a stop watch. In calculating the volume of water discharged, corrections were made for the different temperatures of this discharge.

Observations were taken over periods of from 3 to 12 minutes, depending upon the velocity of the water. During these periods, six readings of the thermometers were made, so that all of the temperatures given in Table 1 are the average of six readings. At the beginning of a period, an observer swung the end of the discharge pipe *B* over a tank previously balanced on a pair of platform scales, and at the same time snapped the stop watch. The temperatures were then read at equal intervals during the period. At the end of the period, the pipe *B* was swung from over the water tank.

Observations were taken for four different temperatures of the steam in the jacket, 210.9°, 274°, 307°, and 330° F., and for each jacket temperature the water velocity was varied from about .4 to 17 ft. per second. In these experiments, no attempt was made to keep the temperature difference constant between the steam in the jacket and the mean temperature of the water.

V. Calculations

Referring to Table 1, column 14, the British thermal units per square foot per minute have been computed from the weight of water per minute, column 12; the rise in temperature of the water, column 4; and the area of the tube, computed from the mean diameter.

The mean temperature of the water, column 10, is the average of the items of columns 2 and 3. The curves of Fig. 2 show that within the temperature range of these experiments, this will be the true mean value.

The formula for the flow of heat through a given medium is similar to that for the flow of an electric current, and may be obtained as follows:

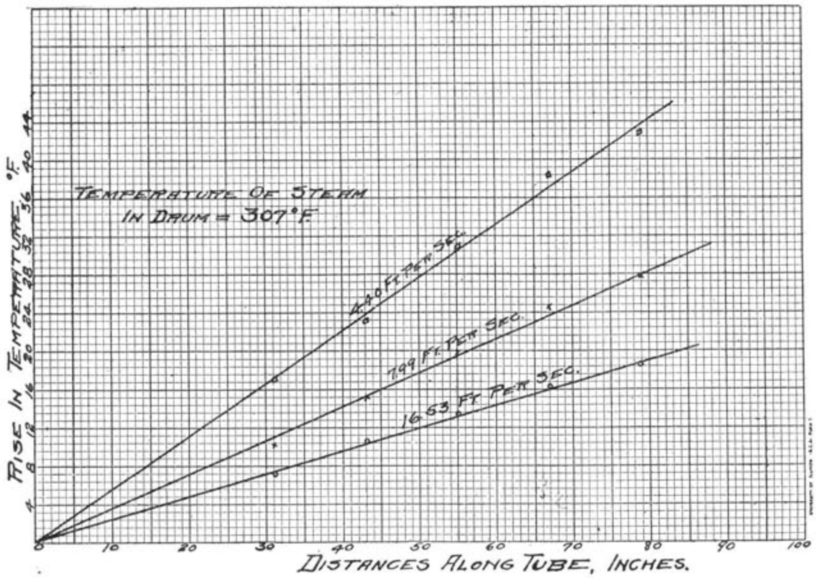


FIG. 2

Let Q = B. t. u. flowing per square foot per second.

$(t - t_1)$ = the temperature drop in degrees F. between two planes cutting the medium parallel to each other, and perpendicular to the direction of flow.

A = area in square feet of a section through which the heat is transmitted.

S = the time in seconds during which the flow takes place.

L = length in inches of the medium or the perpendicular distance between the two planes.

K = the conductivity of the medium, which is equal to the number of B. t. u. transmitted per second, per degree difference in temperature F., per square foot of area per inch of length.

Then $$Q = \frac{(t - t_1) \text{ x } A \text{ x } S \text{ x } K}{L} \ldots\ldots\ldots\ldots (1)$$

The quantity K has been determined experimentally by a number of experimenters, and in c. g. s. units is about .2 for boiler iron. Reducing this to B. t. u., square feet, degrees F., and inches, we obtain the value, $.1612 = K$ = the conductivity of boiler iron. The reciprocal of the conductivity is equal to the specific

resistance $= \dfrac{1.0}{.1612} = 6.2$

In the present case the thickness of the wall of the tube is .134 in. The resistance of the metal of the tube per square foot, therefore, $= 6.2 \times .134 = .831$ and the "conductance" is

$\frac{1.0}{.831} = 1.204$. This value has been assumed to be constant

for the temperatures here used.

It will be well to point out here the distinction between "conductivity" and "conductance", as used in the present article. Conductivity has been used to designate that quantity of heat which will flow through a medium of unit length and of unit area in a unit of time with a temperature drop of one degree, while "conductance" is independent of the length of the medium. The distinction is made necessary on account of the unknown thickness of the steam and water films.

The conductance of the water film, or the B. t. u. transmitted per square foot per second through this film may be determined in the following manner:

Let Q = B. t. u. transmitted per square foot per second.

A = area of the surface of the film in square feet.

S = time in seconds.

K'' = conductance of the water film.

K''_1 = conductivity of the water film.

L'' = thickness of water film, and can not readily be determined.

$(t'' - t''_1)$ = drop in temperature between the inner or water surface of the tube and the water.

$$Q = \frac{K''_1 (t'' - t''_1) \text{ x } A \text{ x } S}{L''} \ldots\ldots\ldots\ldots\ldots (2)$$

and

$$K'' = \frac{K''_1}{L''} = \frac{Q}{(t'' - t''_1) A \text{ x } S} \ldots\ldots\ldots\ldots (3)$$

In order to determine $(t'' - t''_1)$, it will be necessary to determine the temperature of the inner or water surface of the tube. The temperature of the steam surface is given in Table 1, column 6. From formula 1, having Q, which is obtained from Table 1, column 14, and K, given, the temperature drop through the metal of the tube may be computed. This has been done and the results are given in column 8. By subtracting the temperature drop through the metal of the tube from the temperature of the steam surface of the tube, the temperature of the water surface is obtained. This is given in column 9, and the drop from the water surface to the mean temperature of the water is given in column 11. Having this drop, the conductance of the water film may be computed from the formula.

A consideration of the phenomena occurring on the steam side of the tube is foreign to the purpose of this paper. As, however, the application of the results of experiments along this line have already proved of the greatest practical value in the design of high vacuum apparatus, and as our data are so closely related to this side of the problem, that is, the transmission of heat from the steam to the tube, it will probably not be amiss to devote a small amount of space to this phase of the subject.

On the steam side of the tube, if a condition of equilibrium is assumed to maintain, there will be the condition of saturated steam imparting its heat to a film of water on the surface of the tube, which film may be assumed to be of a constant thickness, and which is constantly being replaced or renewed by the condensation of fresh steam. The agitation of the steam in contact with the water film will, therefore, if it does not agitate this film, have no effect upon the rate of heat transmission or the conductance, at least, in the case of the present experiments; for the maximum velocity of approach of the steam towards the tube, due to the condensation, is about $\frac{1}{5}$ ft. per second. This would lead one to believe that the temperature on the surface of separation of the steam from the water film must be practically the temperature of the saturated steam. If such is the case, the agitation of the steam alone would not affect the conductance, as it would not change the temperature drop through the tube. The solution of the problem of more efficient heat transmission from steam to surface of tube, therefore, lies solely in the removal or agitation of the water film.

If it is then assumed that the temperature of the surface of water film in contact with the steam is at the temperature of the steam, and that the temperature of the surface of the water film in contact with the tube is at the temperature of the tube, the conductance of the water film on the steam side of the tube may be computed from the following:

Let K' = conductance of the film.
K'_1 = conductivity of the film.

L' = thickness of film in inches.

A = area of surface of film in square feet.

S = time in seconds.

Q = B. t. u. transmitted per square foot per second.

$(t' - t'_1)$ = temperature drop between steam in jacket and outer surface of tube, as obtained by thermocouples.

$$Q = \frac{K'_1 (t' - t'_1) A \text{ x } S}{L'} \ldots\ldots\ldots\ldots\ldots\ldots (4)$$

therefore

$$K' = \frac{K'_1}{L'} = \frac{Q}{(t' - t'_1) \text{ x } A \text{ x } S} \ldots\ldots\ldots\ldots (5)$$

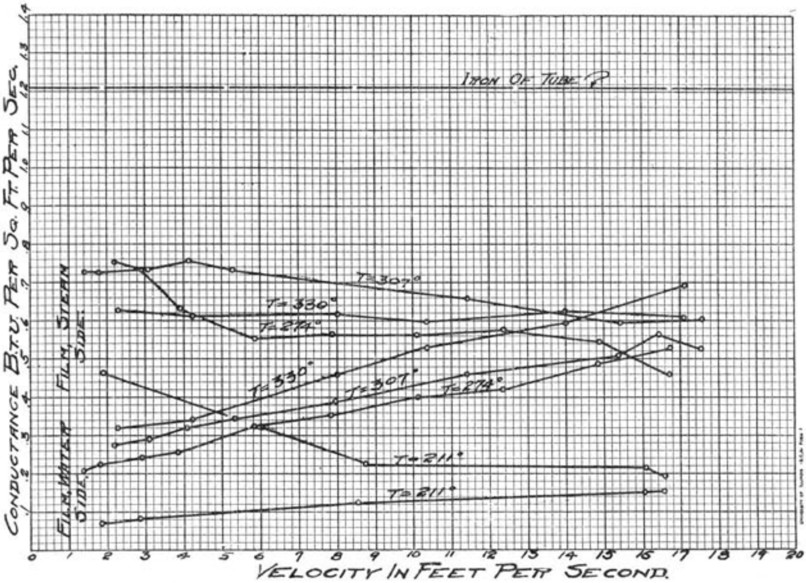
In the above formula A and S may be taken as unity; Q is obtained from Table 1, column 14; the values here given are expressed in B. t. u. per minute and must be reduced to B. t. u. per second before being used in the formula.

$(t' - t'_1)$ is taken from column 7 of the same table.

The value of L' can not be determined.

The conductances of the water films on the steam and water sides of the tube are given in columns 15 and 16, respectively, and these results are shown plotted against the velocity in feet per second of the water in the tube, Fig. 3. The temperatures placed on these curves are the temperatures in the steam jacket during each experiment. The data from which the points on the 211° curve were plotted were taken from the results of some later experiments, and have not been included in the table.

It will be seen from this figure, that the conductance of the film on the water side increases with the velocity of the flow of the water in the tube. This increased conductance at the higher velocities, which means a higher rate of agitation of the water, is due to the increased number of particles of the water coming in contact with the walls of the tube. The word "conductance" used to express the flow of heat from tube to water is somewhat inappropriate in this place, for it seems to suggest that the film remained the same so far as its physical structure was concerned, and that its heat conductivity varied, while as a matter of fact, the increased conductance or the increased flow of heat from the tube to the water at the higher velocities is due to the destruction or rather to the continuous renewal of this film. In the case of water flowing in a tube at velocities lower than the critical ve-



locity, where the stream lines are parallel, we can consider that this stream of water is made up of concentric cylinders of water, the central cylinder of which is moving at the highest velocity, and the velocity of the outer cylinders gradually drops off until the lowest velocity is found in that cylinder which is in direct contact with the walls of the tube. In this case, the heat flow from the walls of the tube takes place principally by conduction, and the effect of convection is very small. The case is analogous to that of heating water in a vessel from the top, such as has been used for the determination of the specific conductivity of water and other liquids. When the critical velocity of the water in the tube is reached, or when baffles are placed so as to disturb the parallelism of the stream lines, the concentric cylinders of water disappear and the stream lines mingle and flow from side to side in zigzag fashion; the film of water adjoining the tube walls is being continually renewed by these zigzag stream lines, and the flow of heat from tube to water is carried on largely by convection.

The conductance of the film on the steam side has been computed and the results are given in column 15 of the table. These conductances have also been plotted against the velocity of flow of the water in the tube and are shown in Fig. 3.

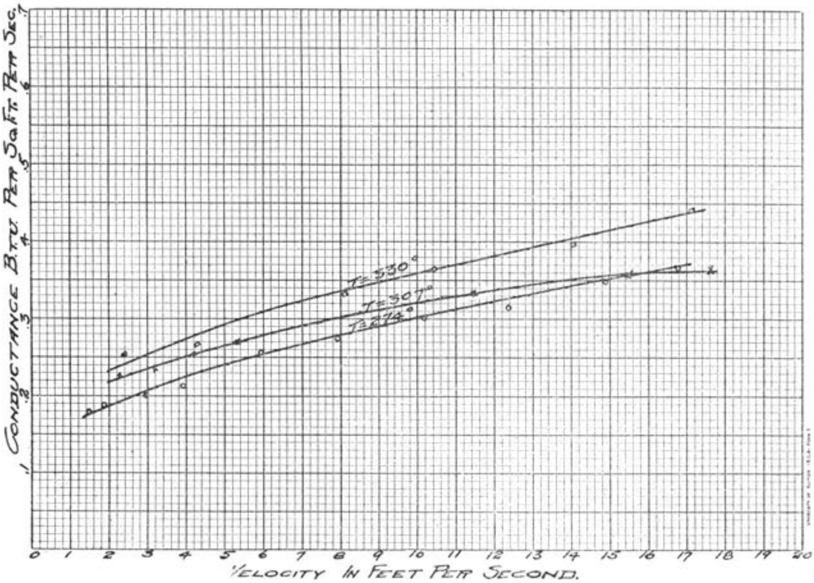

Conductance B.T.U. Per Sq. Ft. Per Sec.
T=330°
T=307°
T=274°
Velocity In Feet Per Second.

Fig. 4

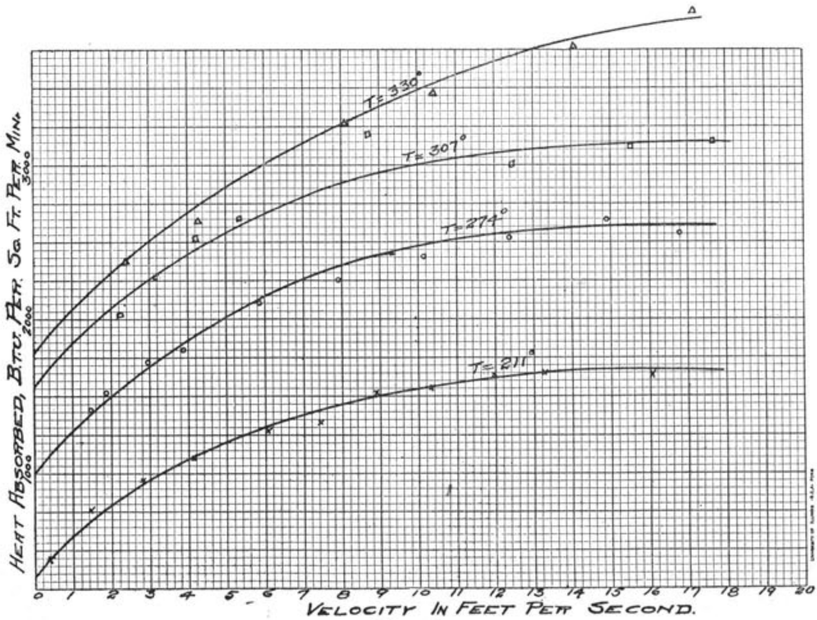
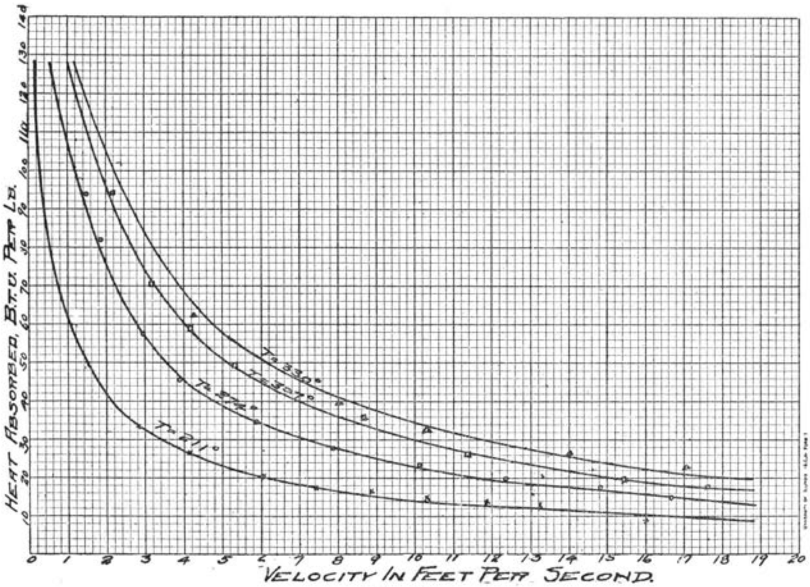
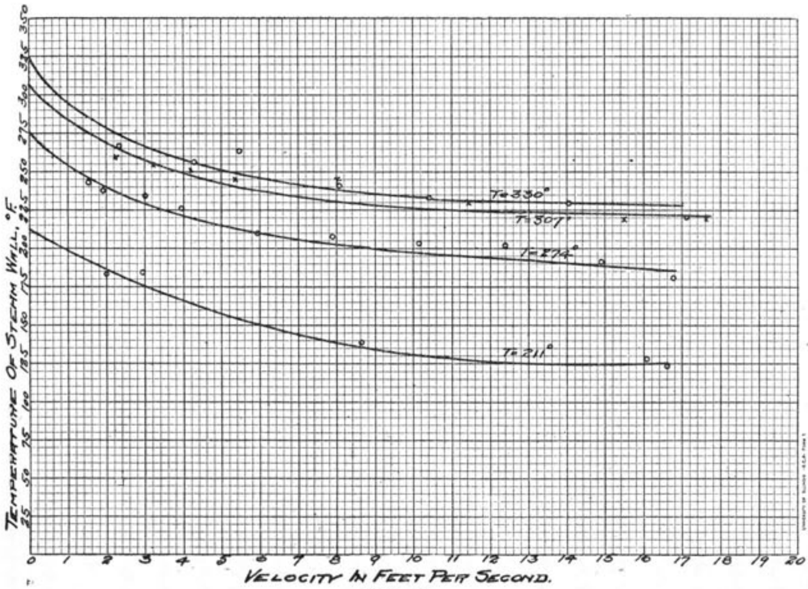

Heat Absorbed, B.T.U. Per Sq. Ft. Per Min.
T=330°
T=307°
T=274°
T=211°
Velocity In Feet Per Second.

Fig. 5



HEAT ABSORBED, B.T.U. PER LB.
VELOCITY IN FEET PER SECOND.
T=330°
T=307°
T=274°
T=211°

Fig. 6



TEMPERATURE OF STEAM WALL, °F.
VELOCITY IN FEET PER SECOND.
T=330°
T=307°
T=274°
T=211°

Fig. 7

It will be noted that the conductance of the steam film increases as the velocity of the water in the tube decreases. This is doubtless due to the decrease in temperature difference between the steam and the water as the velocity of the latter is decreased. This results in less condensation on the tube, consequently a thinner layer or water film on the surface of the tube, which makes a higher conductance possible.

The curve taken with a steam temperature of 330° in the jacket is almost a straight line. The other curves also tend to assume a straight line at the higher velocities, which means at the higher temperature differences. It is possible that the former curve would rise suddenly at the smaller velocities.

In Fig. 3 is also shown the straight dashed line indicating the constant conductance of the metal of the tube, which is 1.204.

In column 17 of the table, are given the conductances through tube and film on the water side. These were computed by taking the reciprocal of the sum of the reciprocals of the conductances of the tube and of the film on the water side; the former of which is constant and equal to 1.204, while the latter is obtained from column 16 of the table. The conductances of tube and film are shown in Fig. 4 plotted against the velocity of flow of the water.

The curves of Fig. 5 show the relation between the velocity of the flow of the water in the tube and the total heat transmitted per minute per square foot of mean tube surface. Curves of Fig. 6 show the relation between the velocity of the water and the B. t. u. absorbed per pound. The curves of Fig. 2 were obtained by a set of separate experiments to investigate the rise in temperature of the water along the tube. The temperatures in the tube were taken by means of a thermocouple placed in the end of a long glass tube which was pushed through a perforated cork placed in the end of the water or boiler tube. Beyond the end of the glass tube and ahead of the thermocouple junction, a small baffle was placed so that the mean temperature of the water might be obtained. It will be seen that the rise in temperature is proportional, within the limits of these experiments, to the distance from the entering end of the tube.

In Fig. 7, the temperature of the steam surface of the tube is plotted against velocity of water in feet per second. These curves by their uniformity seem to indicate the reliability of this method of experimentation.

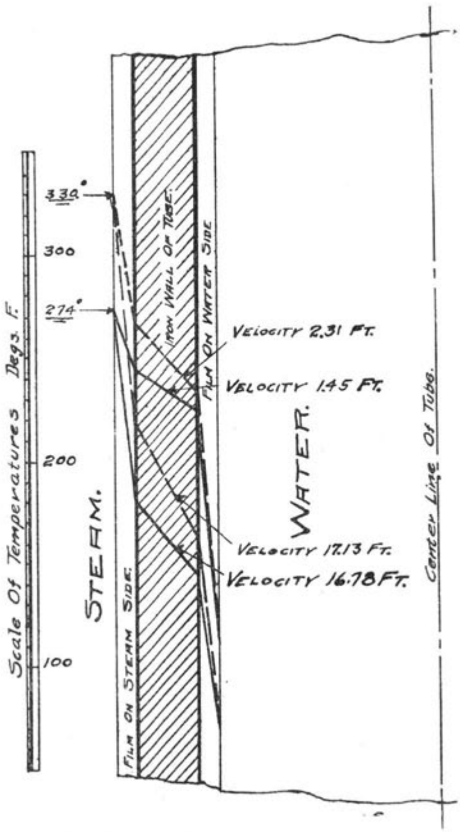


FIG. 8

Fig. 8 is a graphical representation of the temperature gradient through the film on the steam side, the tube and the film on the water side. The values corresponding to the maximum and the minimum velocities, as obtained in the experiment, have been plotted for the steam temperatures of 330° and 274° maintained in the jacket. Fig. 8 illustrates the increased temperature gradient due to the increase of the velocity of flow of the water in the tube. Fig. 8 is interesting in several respects. It illustrates very clearly the effect and importance of the film resistance in all heat transmission problems. It further shows that the film resistance of the metal in the case of tube and plates is much less than the resistance of the films. It may even be used to illus trate why it is possible to lubricate a gas engine with cylinder oil having a flash point of 700° F. while the temperature of the gases in the cylinder may be close to 2500° F.

VI. Conclusions

The limited nature of these experiments forbids the drawing of any general conclusions other than those already known. The principal interest lies in the development of a method which seems to offer a very desirable means of studying the effect of the variation of the velocity of the flow of gas, steam or water on the rate of flow of heat through tubes, plates, etc.

In order to investigate this subject of the effect of velocity on heat transmission more carefully, means should be provided for maintaining the tube and the water at a constant temperature, while varying the velocity of the latter. In studying the effect on the heat transmission of the velocity of gases over the tube, means should be provided for varying the velocity of the gas, while maintaining a constant temperature of the gas and the tube.

The effect of the formation of steam on the walls of the tube, as it approaches the condition in steam boiler practice, should come in for consideration. It is probable that the effect of rapid agitation of the water in a tube in which steam is forming, especially in large quantities, will be much greater on the heat transimssion through the tube to the water, than would be the case in a tube in which no steam was forming, owing of course, to the breaking up and washing off of the steam bubbles from the side of the tube. It might be well to point out here that it is the rate of agitation, and not necessarily the velocity of the water that produces the change in heat transmission. The velocity in feet per second has been used for the reason that it is the only definite quantity available to express this rate of agitation. It may be, to a certain extent, a measure of the rate of agitation, but it is not necessarily so. The rate of agitation may be defined as the number of times per second that each particle of water comes into contact with the tube or with the film on the tube if we consider that the film is indestructible, although it is more likely that the film is in a process of continuous renewal. In the case of the present experiments, it is probable that if elaborate baffles had been placed in the tube, the heat transmission for the same velocity of flow would have been increased. Also, if the stream of water on entering the tube had been given a rotary motion, the heat transmission would have been increased while the velocity through the tube remained constant.

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